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An Ensemble Empirical Mode Decomposition Approach for Voltage Sag Detection in a Smart Grid Context

Yassine Amirat^{1,2}, Mohamed Benbouzid², Tianzhen Wang³ and Sylvie Turri²

Abstract—Smart grids have become a focal point in renewable energy source researches. Sustainability and viability of distributed grids are highly dependent on the reduction of the operational and maintenance costs. The most efficient way of reducing these costs would be to continuously monitor the condition of these systems. This allows for early detection of the power quality degeneration, and facilitating a proactive response, prevent a fault ride-through the renewable energy conversion system, minimizing downtime, and maximizing productivity. This paper provides then the assessments of an advanced signal processing technique, namely the ensemble empirical mode decomposition, using the instantaneous power for voltage sags detection in smart grids. *Copyright © 2013 Praise Worthy Prize S.r.l. - All rights reserved.*

Keywords: Smart grid, voltage sag detection, power quality (PQ), ensemble empirical mode decomposition (EEMD).

I. Introduction

Renewable energy conversion systems are the fastest-growing sources of new electric generation in the world and it is expected to remain so for sometimes, and those sources are becoming a reliable competitor of classical power generation systems, which are facing to constantly changing operating parameters, such as fuel cost, multiple fuel tradeoffs and maintaining older systems becomes more costly; and actually a volte-face is made against nuclear power station that can cause human disaster. These systems offer an alternative and emerging solution by deploying hybrid power plant offshore or onshore, where there are substantial renewable resources, leading to a best electricity generating opportunities. With the deployment of distributed renewable power generation; the electricity networks are undergoing wholesale changes both from generation and the user sides. Unlike the classic power plants which are far from the user, the actual tendency is to move generation system nearby the distribution level and this can be achieved by using a set of micro grids and energy islands based on renewable sources, connected to the main grid as illustrated in Fig. 1 [1-2]. Hence, this topology allows micro grids parallel operation to main grid or isolated as an energy island. This philosophy requires flexible micro grids that will be able to meet the power demand needs and have islanding fast capabilities when a fault occurs such as voltage sags or power outage; this is known as a smart grid. So, key considerations when deploying smart grids are their availability, reliability, and profitability; in order to fulfill power demand according to PQ standards. In this context, voltage sags automated detection is indexed as an essential requirement for a condition monitoring system in order to meet PQ standards [3-6].

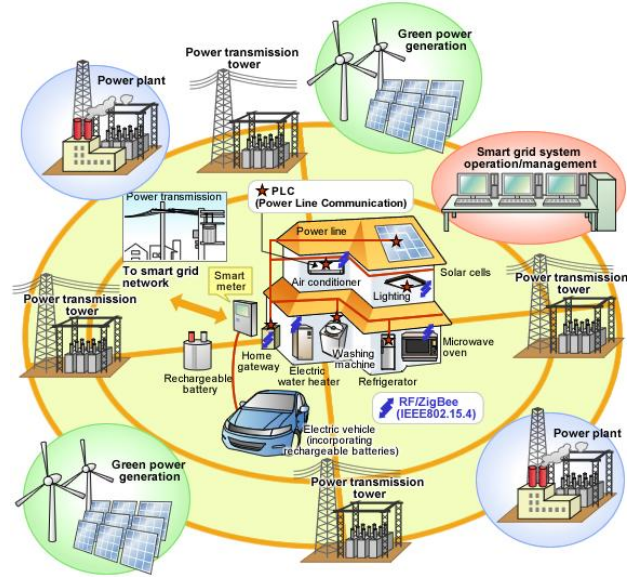


Fig. 1. Smart grid general topology [© RENESAS].

So, a deep knowledge about all the phenomena involved during the occurrence of voltage sag constitutes an essential background for the development of any condition monitoring systems. Regarding a fault as a particular input acting on a power system (grid), a detection system must be able to detect its occurrence, as well as to isolate it from all other inputs such as disturbances and controls affecting the behavior of the system.

It is therefore obvious that monitoring is a key issue that needs to be addressed to make a grid more intelligent. This requires much more sophisticated computer-oriented monitoring than in a classical grid [1].

In this context, signal processing is certain to play a significant role in dealing with the complexity and uncertainty associated with a smart grid [7]. This paper provides then the assessment of an advanced signal processing technique; namely the ensemble empirical mode decomposition (EEMD). EEMD is mainly a signal processing technique to extract distinctive features; namely intrinsic mode functions (*IMFs*). Feature selection requires a series of calculations based on statistics such as maxima, minima, singular value, standard deviation, and mean [8]. The instantaneous power will be used as the electrical quantity for voltage sag detection [9].

II. Voltage Sags Characterization

Voltage sags are defined as a deviation of the RMS supply voltage from a reference value with typical dip depths ranging from 0.9 to 0.5 pu of a 1 pu nominal [10]; lasting from few milliseconds to few cycles, unlike *under voltage* or *over voltage* that occur for long periods. Voltage sags are therefore a transient voltage amplitude deviation. They are caused by abrupt increases in loads such as phase to phase or phase to ground short circuits, they are also caused by abrupt increases in source impedance, typically caused by a loose connection.

The most usual voltage sags signatures are depicted in Fig. 2 [11]. During a voltage sag three-phase system balanced conditions are no longer valid leading to possible disastrous consequences on the user end-loads and on the smart grid itself.

Voltage sag characterization concerns events quantification through a limited number of parameters. These parameters depend on the field of study. However, main characterization methods use two parameters to determine the severity of a voltage sag: magnitude (or “remaining voltage”) and duration [3].

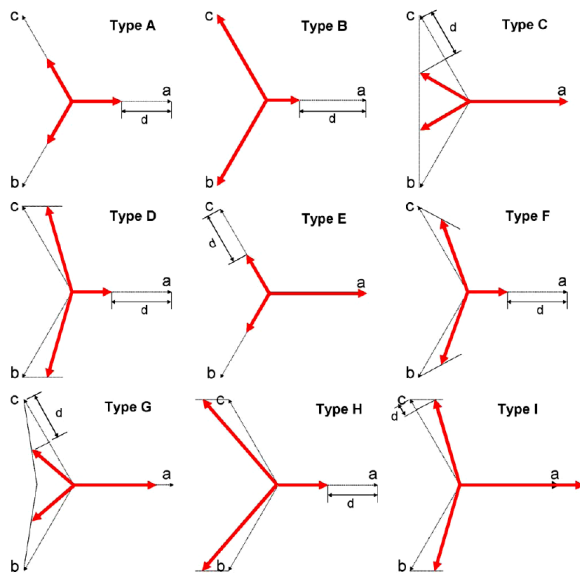


Fig. 2. Voltage sag main signatures [4].

In the context of a smart grid, it is therefore important to know whether voltage sag exists and afterward estimate its duration.

III. Voltage Sags Detection

III.1. Brief Review

For voltage sag detection, there is a wide range of technology and methods derived from contemporary power systems where condition monitoring systems use pre-installed sensors that are managed together in different architectures and coupled with algorithms to allow a smart grid efficient monitoring [11-14].

Well-established methods are those based on electrical quantity signatures analysis (current, voltage, power, etc.). Indeed, those quantities are easily accessible or evaluated during operation. Electrical quantities analysis usually involves the use of reference frame transformations such as Park's vector [13] or three-phase system symmetrical components or space vector [4], and other techniques based upon them. These techniques however assume that voltage and current quantities are pure sine waves, while in real-world the electrical quantities are polluted by harmonics produced by power electronic devices in both sides of the smart grid, and transient spikes due to grid apparatus maneuvers. It is therefore obvious the Fast Fourier Transform (FFT), and other techniques based upon it, are no longer valid even they has been used in some cases [10]. Advanced signal processing techniques are therefore required to deal with the complexity and uncertainty associated with a smart grid. In [15], a Teager-Kaiser energy operator has been proposed for power system oscillations detection and analysis. However, this operator is highly affected by noises.

III.2. EEMD Approach

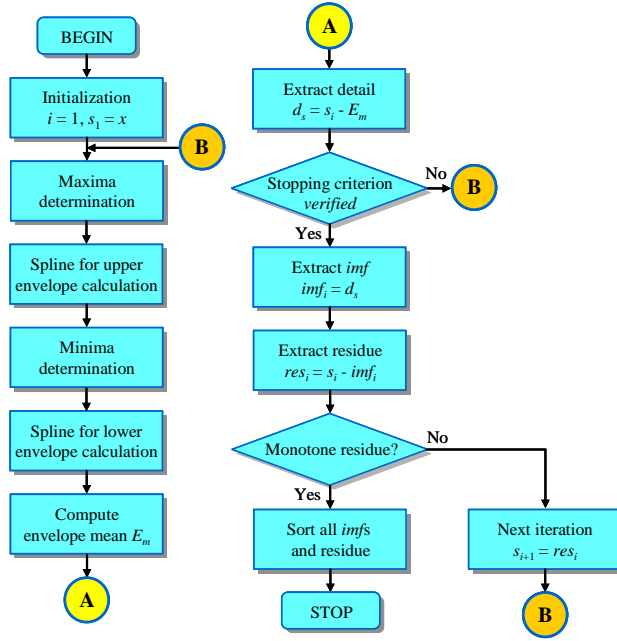
It seems that one of the emerging methods for transient signal processing is the empirical modal decomposition (EMD) [6]. The EMD method has focused considerable attention and has been indexed recently for power system fault detection and analysis [15-16]. Indeed and contrary to well-known decomposition techniques, EMD is intuitive and direct, with the basic functions based on and derived from the data.

The EMD is an adaptive time-frequency data analysis method for nonlinear and non-stationary signals. It is used to decompose the multi-component signal into a series of Intrinsic Mode Function (*IMFs*) based on the signal time-scale local characteristics. It decomposes the signal into a number of *IMFs* that are mono-component function. The multi-components signal (the electrical quantity x to be chosen) is then decomposed into M intrinsic modes and a residue R_M .

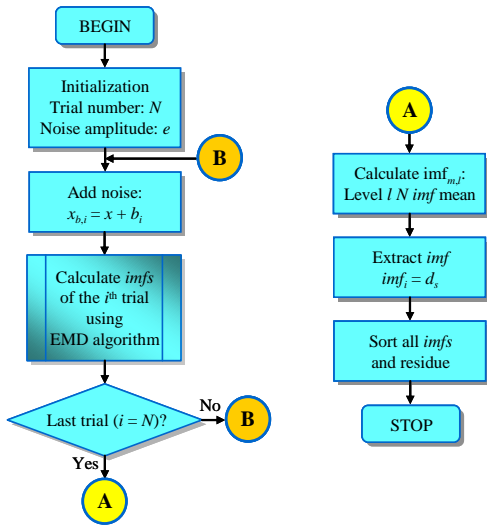
$$x(n) = \sum_{m=1}^M IMF_m(n) + R_M(n) \quad (1)$$

The procedure for extracting the $IMFs$ from a signal is illustrated in Fig. 3a.

However, one major drawback of the EMD is the mode mixing. This phenomenon means that the detail related to one scale can appear in two different intrinsic modes. To overcome this drawback, the EEMD was introduced [17]. The EEMD is described as a new noise-added method, which mitigate automatically the EMD mode-mixing. The EEMD procedure for extracting the $IMFs$ from a signal is illustrated in Fig. 3b.



(a) EMD algorithm flowchart.



(b) EEMD algorithm flowchart.

Fig. 3. EEMD decomposition process.

IV. Evaluation of the EEMD-Based Voltage Sags Detection Approach

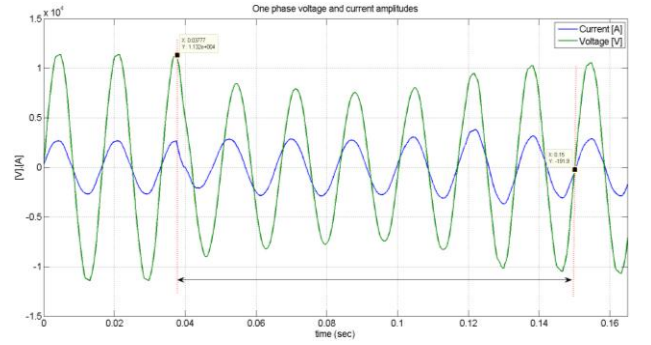
In order to assess the ability of the proposed approach to detect voltage sag, real data were used. Those data were fed by the DOE/EPRI National Database Repository of Power System Events [18].

Figure 4 clearly shows that voltage sag in a three-phase system produces a voltage dip in each phase with a sharp variation in the current amplitude and a phase-shift.

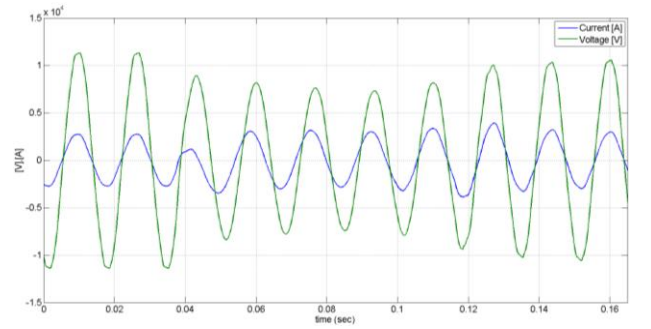
Since voltage sag effect arises in voltages v and currents i , it seems more relevant to use the three-phase instantaneous power given by

$$p(t) = \sum_{k=a,b,c} v_k(t) i_k(t) \quad (2)$$

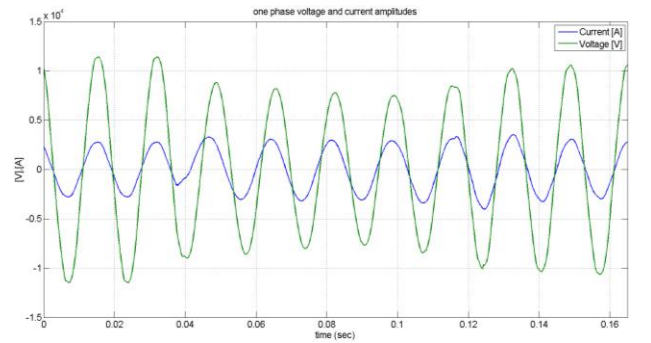
to investigate voltage sag occurrence.



(a) Phase a.



(a) Phase b.



(a) Phase c.

Fig. 4. Voltage and current before, during and after voltage sag.

For illustration, Fig. 5 clearly shows that the instantaneous power is a key variable to monitor a smart grid regarding voltage sag. Indeed, it contains the above-mentioned relevant parameters (§ II: fault appearance time and duration).

After decomposing the instantaneous power according to the EEMD algorithm, several *IMFs* were obtained as shown by Fig. 6. The *IMFs* analysis obviously show that the 4th seems the more impacted by the voltage sag. In particular, this *IMF* is very sensitive to the fault occurrence and its duration. It is therefore chosen as the key *IMF* for voltage sags detection (Fig. 7).

This is confirmed when intrinsic modes decomposition is carried-out during a phase voltage cycle that corresponds to 16.66 msec or 128 samples of the instantaneous power. Indeed, this is illustrated by Figs 8 and 9 that show respectively the instantaneous power amplitude and the 4th *IMF* for each processing interval.

The shortest path to the 4th *IMF* amplitude information is the statistic variance σ^2 given by

$$\sigma_{imf_4}^2 = \frac{1}{N} \sum_{n=0}^{N-1} [IMF_4(n) - \mu_{IMF_4}]^2 \quad (3)$$

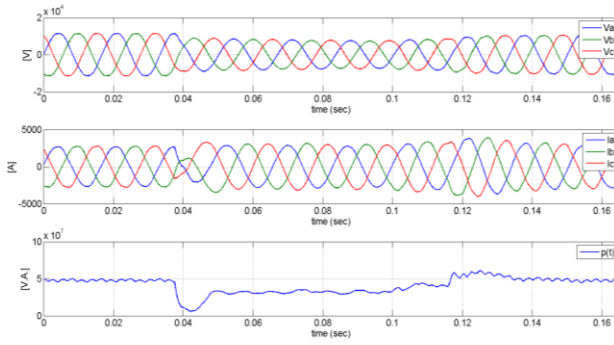


Fig. 5. Phase voltages, currents, and the total instantaneous power before, during and after voltage sag.

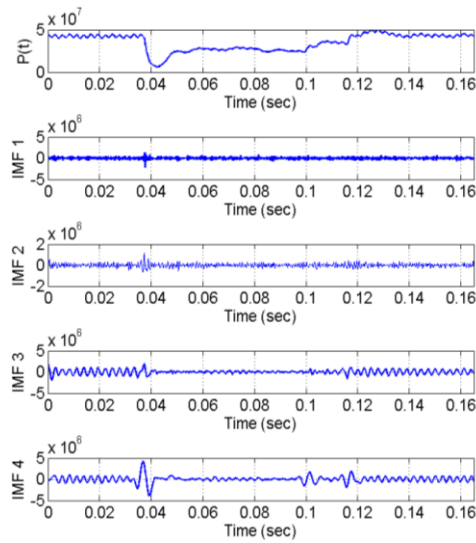


Fig. 6. The instantaneous EEMD decomposition.

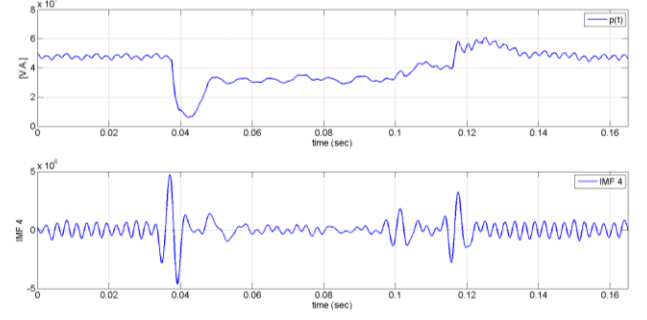


Fig. 7. Instantaneous power and its 4th *IMF* before, during and after voltage sag.

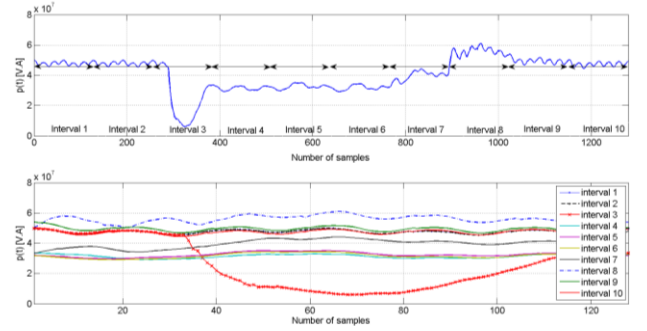


Fig. 8. Instantaneous power during each processing interval.

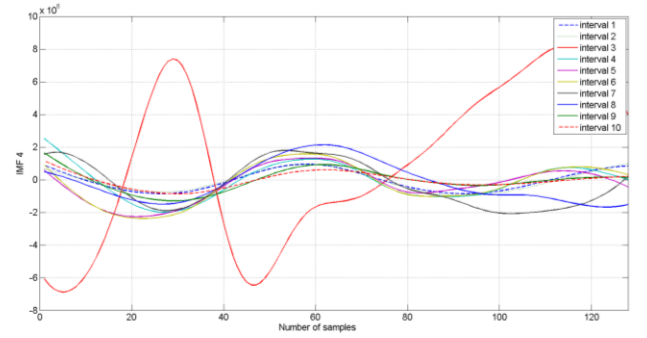
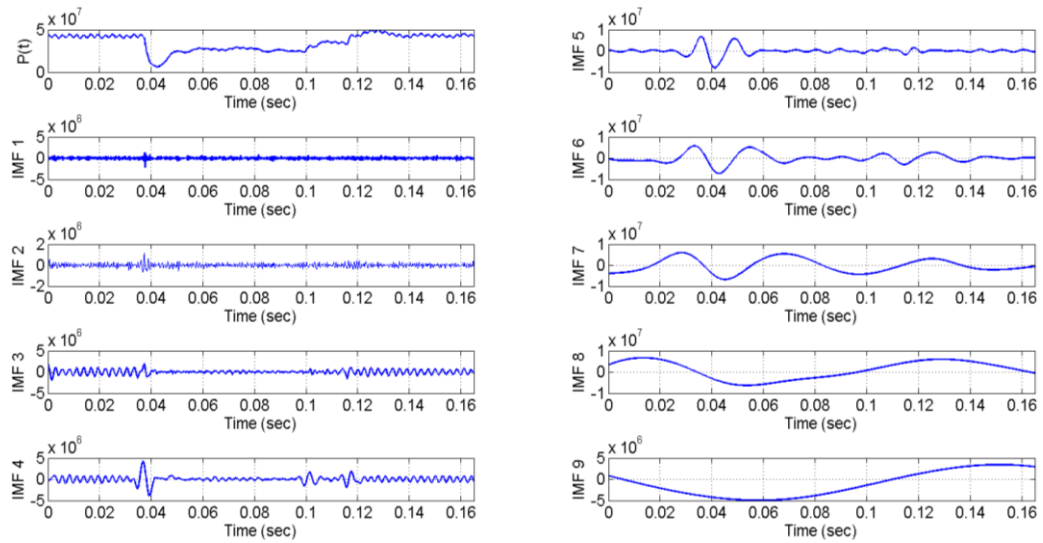


Fig. 9. Instantaneous power 4th *IMF* for each processing interval.



After the EEMD processing, the 4th IMF variance is computed in each interval and collected in Table 1.

According to the electrical quantities waveforms, for the 1st and 2nd voltage cycles, normal operation is confirmed by the variance reduced and constant value ($\sigma^2 = 3.8\%$) in the 1st and 2nd intervals. At a voltage sag occurrence (3rd cycle), the variance obviously increases to 234.48% and remains between 11% and 14% during the voltage sag. Afterward, it decreases to a small value at the 9th and 10th intervals. It is therefore clearly demonstrated that the 4th IMF can be used as the prime variable for monitoring voltage sags in terms of detection and duration estimation using a grid voltage cycle as time-base.

V. Conclusion

This paper dealt with voltage sag detection in a smart grid using the instantaneous power quantity. This quantity was first decomposed into intrinsic mode functions through the EEMD. It was then found that the 4th is the more sensitive to the fault occurrence and its duration. The 4th IMF mode was then analyzed using a statistic criterion based on the variance. The achieved results clearly show that it can be used an effective indicator for voltage sag detection and smart grid monitoring. However, one of the EEMD major drawbacks is the lack of theoretical background. Indeed, this can be useful for the comprehension of all phenomena occurring during voltage sag.

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- ¹ISEN-Brest, 20, Rue Cuirassé Bretagne, CS 42807, 29228 Brest Cedex 2, France. (e-mail: Yassine.Amirat@isen.fr).
- ²University of Brest, EA 4325 LBMS, Rue de Kergoat, CS 93837, 29238 Brest Cedex 03, France (e-mail: Mohamed.Benbouzid@univ-brest.fr, Sylvie.Turri@univ-brest.fr).
- ³Shanghai Maritime University, Department of Electrical Automation, 201306 Shanghai, China (email: tzwang@shmtu.edu.cn).

Table 1. 4th IMF variance.

Interval	1	2	3	4	5	6	7	8	9	10
σ^2	3.80%	3.80%	234.43%	11.01%	11.08%	14.25%	18.36%	14.37%	4.36%	2.05%



Yassine Amirat was born in Annaba, Algeria, in 1970. He received the B.Sc. and M.Sc. degrees both in electrical engineering, from the University of Annaba, Algeria, in 1994 and 1997 respectively. In 2011, he received the PhD degree in electrical engineering from the University of Brest, Brest, France.

Dr. Amirat was a Lecturer in the University of Annaba, Annaba, Algeria and then in the Institut Supérieur de l'Electronique et du Numérique (ISEN), Brest, France. Since

January 2012, he is an Associate Professor of electrical engineering. His current research interests are the condition monitoring and the control of electrical drives and power electronics.



Mohamed El Hachemi Benbouzid was born in Batna, Algeria, in 1968. He received the B.Sc. degree in electrical engineering from the University of Batna, Batna, Algeria, in 1990, the M.Sc. and Ph.D. degrees in electrical and computer engineering from the National Polytechnic Institute of Grenoble, Grenoble, France, in 1991 and 1994, respectively, and the Habilitation à Diriger des Recherches degree from the University of Picardie "Jules Verne," Amiens, France, in

2000.

After receiving the Ph.D. degree, he joined the Professional Institute of Amiens, University of Picardie "Jules Verne," where he was an Associate Professor of electrical and computer engineering. Since September 2004, he has been with the Institut Universitaire de Technologie de Brest, University of Brest, Brest, France, where he is a Professor of electrical engineering. His main research interests and experience include analysis, design, and control of electric machines, variable-speed drives for traction, propulsion, and renewable energy applications, and fault diagnosis of electric machines.

Prof. Benbouzid is an IEEE Senior Member. He is the Editor-in-Chief of the International Journal on Energy Conversion (IRECON). He is also an Associate Editor of the IEEE TRANSACTIONS ON ENERGY CONVERSION, the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, the IEEE TRANSACTIONS ON SUSTAINABLE ENERGY, and the IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY. He was an Associate Editor of the IEEE/ASME TRANSACTIONS ON MECHATRONICS from 2006 to 2009.



Tianzhen Wang was born in China, in 1978. She received the Ph.D. degree in electrical engineering from the Shanghai Maritime University, Shanghai, China, in 2006.

After receiving the Ph.D. degree, she joined the Department of Electrical Automation of the Shanghai Maritime University, Shanghai, China, in 2006 as an Associate Professor. From 2007 to 2008, she held a post-doc position at the French Naval Academy, Brest, France. Her main research

interests are in the field of fault detection and diagnosis, data mining, and intelligent information processing.



Sylvie Turri was born in France, in 1972. She received the M.Sc. degree in electrical engineering from the University of Nancy, Nancy, France, in 1996. She was awarded the Ph.D. degree in electrical engineering from the University of Franche-Comté, Belfort, France in 2000.

After receiving the Ph.D. degree, she joined the Ecole Nationale Supérieure of Cachan and the SATIE Lab (UMR CNRS 8029) at Rennes, France, as a Teaching and Research Associate. In 2004, she joined the Institut Universitaire de Technologie of Aix-Marseille, University of Marseille III, Marseille, France, as an Associate Professor of electrical engineering. She was appointed to the LSIS Lab (UMR CNRS 6168). In 2006, she joined the Institut Universitaire de Technologie de Brest, University of Brest, Brest, France, as an Associate Professor of electrical engineering, and a member of the LBMS Lab (EA 4325). Her main research interests are in the field of electromechanical systems (power generation, fault diagnosis).